No littering!

WE DON'T NEED YOUR STINKIN' TRASH
We don't Dump trash where You Live
I'm Bitter about Litter

Bjarne Stroustrup

Morgan Stanley, Columbia University

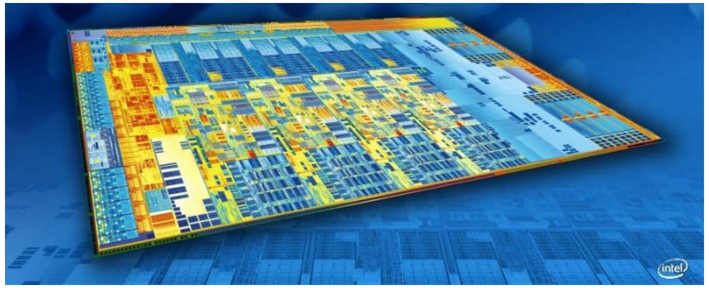
www.stroustrup.com

Executive summary

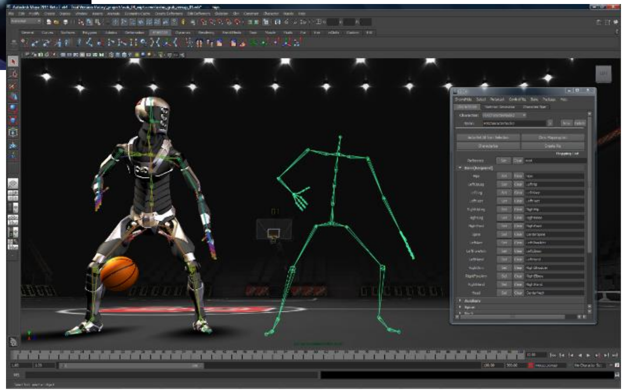
- We now offer complete type- and resource-safety
  - No memory corruption
  - No resource leaks
  - No garbage collector (because there is no garbage to collect)
  - No runtime overheads (Except where you need range checks)
  - No new limits on expressibility
  - ISO C++ (no language extensions required)
  - Simpler code
- Support
  - C++ Core Guidelines: https://github.com/isocpp/CppCoreGuidelines
  - GSL: https://github.com/microsoft/gsl
  - Static analysis/enforcement: In Microsoft Visual Studio
- We want “C++ on steroids”
  - Not some neutered subset

I ♥
C++

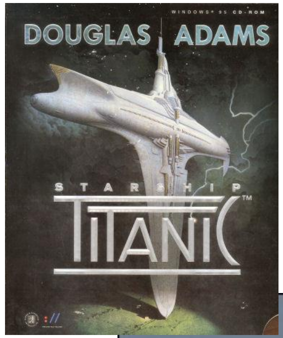
Caveat: Not yet deployed at scale ☹



C++ use



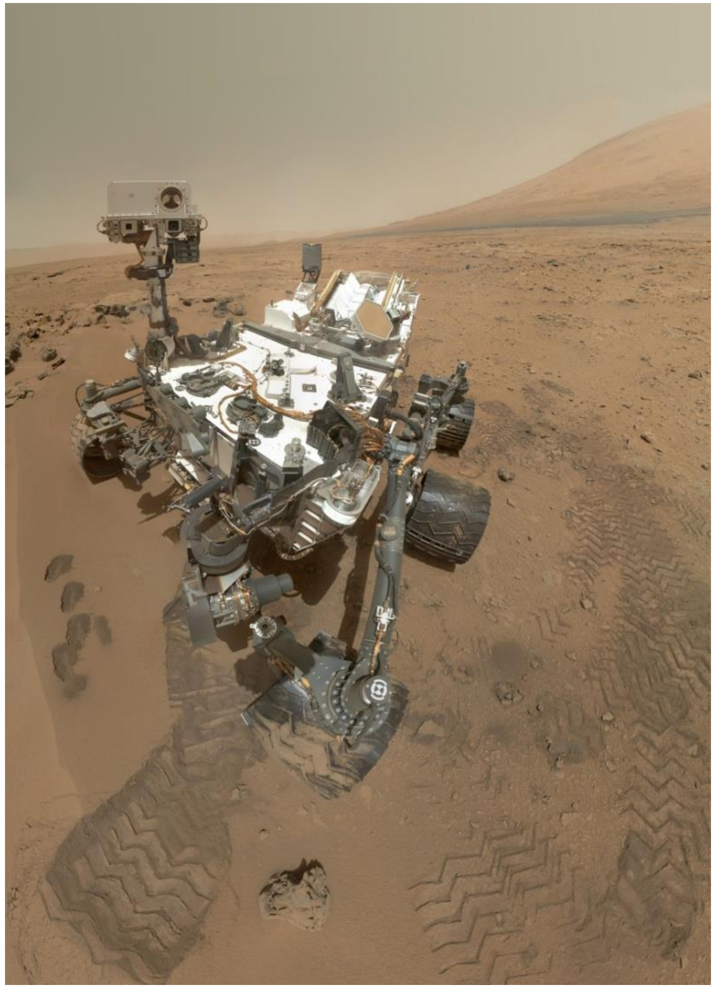
- About 4.5M C++ developers
- 2014-2015: increase of 200,000 developers
- www.stroustrup.com/applications.html



The big question

- **“What is good modern C++?”**
  - ***Many*** people want to write ”Modern C++”
- What would you like your code to look like in 5 years time?
  - “Just like what I write today” is a poor answer
- Guidelines project
  - https://github.com/isocpp/CppCoreGuidelines
  - Produce a ***useful*** answer
    - Implies tool support and enforcement
  - Enable ***many*** people to use that answer
    - For most programmers, not just language experts

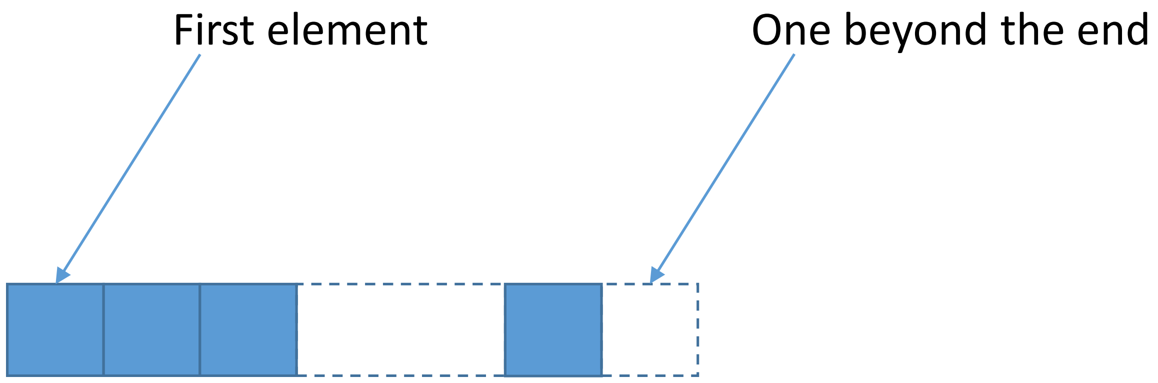
Overview

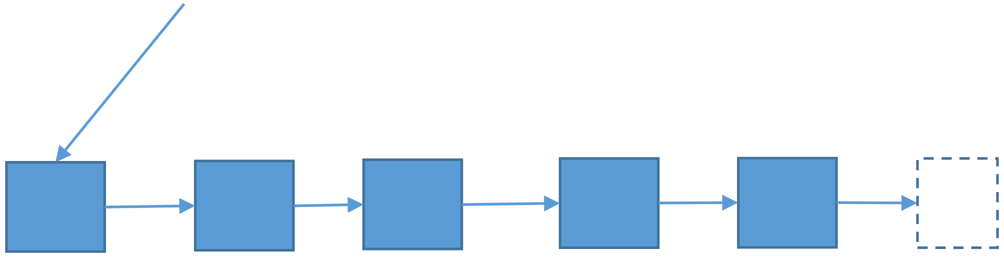


- Pointer problems
  - Memory corruption
  - Resource leaks
  - Expensive run-time support
  - Complicated code
- The solution
  - Eliminate dangling pointers
  - Eliminate resource leaks
  - Library support for range checking and **nullptr** checking
  - And then deal with casts and unions

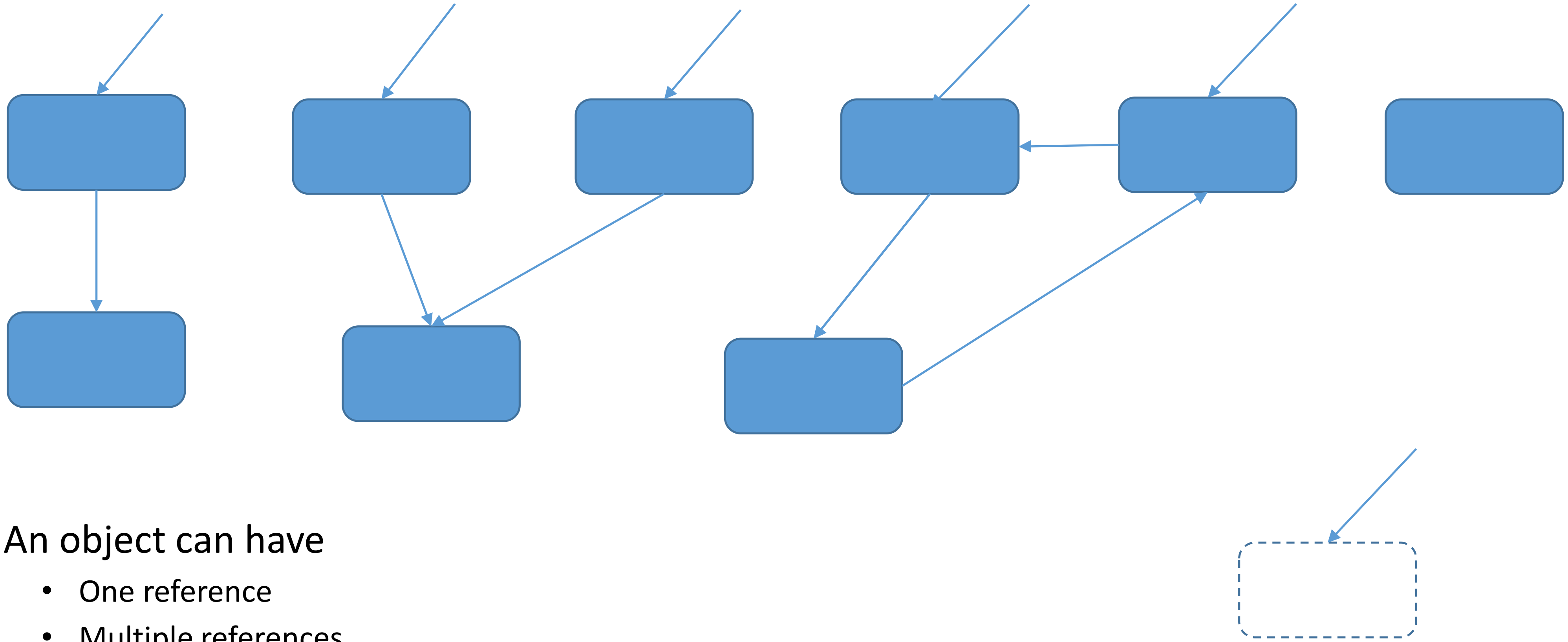
I like pointers!

- Pointers are what the hardware offers
  - Machine addresses
  - For good reasons
    - They are simple
    - They are general
    - They are fast
    - They are compact
- C’s memory model has served us really well
  - Sequences of objects
- But pointers are not “respectable”
  - Dangerous, low-level, not mathematical, …
  - There is a huge ABP crowd



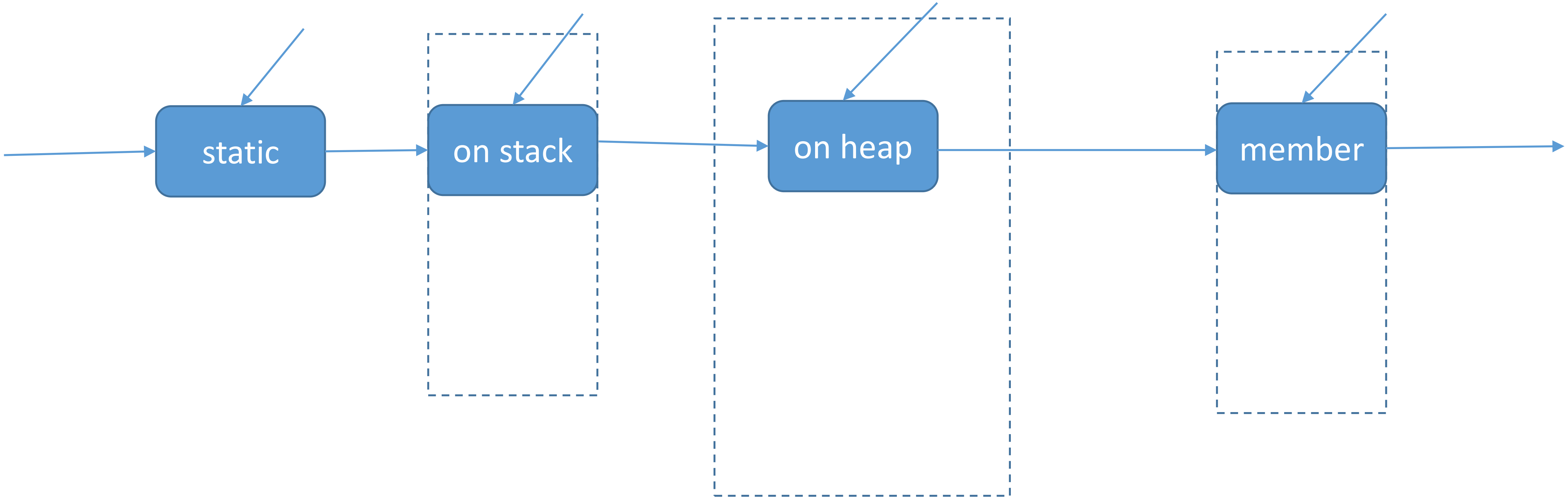


Lifetime can be messy



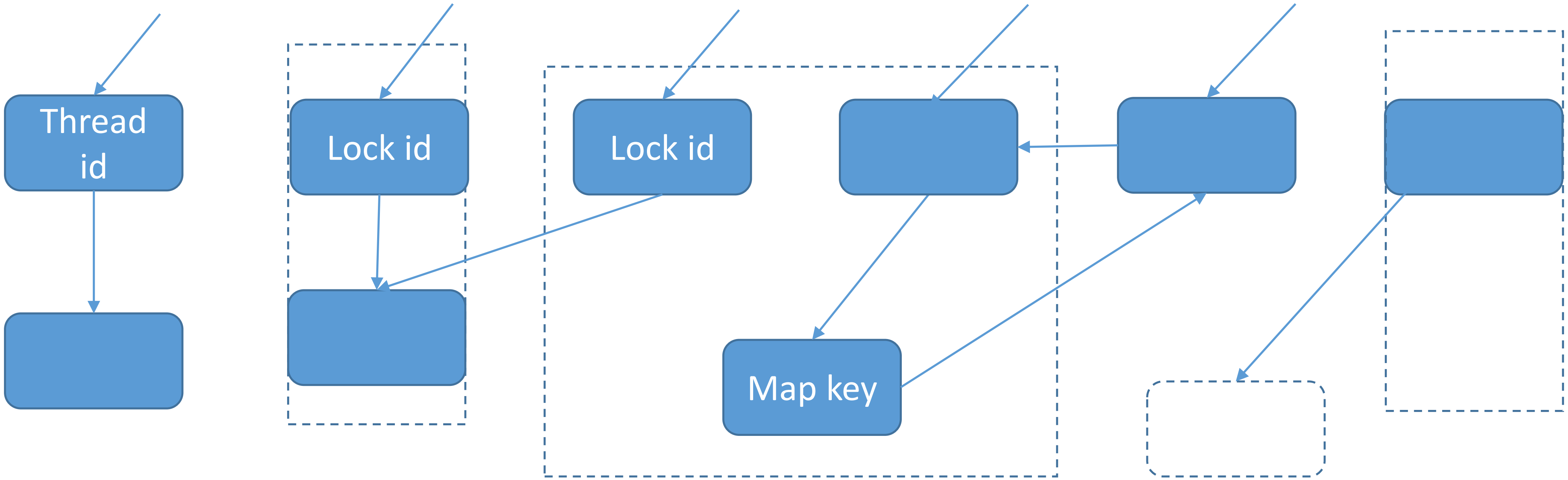
- An object can have
  - One reference
  - Multiple references
  - Circular references
  - No references (leaked)
  - Reference after deletion (dangling pointer)

Ownership can be messy



- An object can be
  - on stack (automatically freed)
  - on free store (must be freed)
  - n static store (must never be freed)
  - in another object

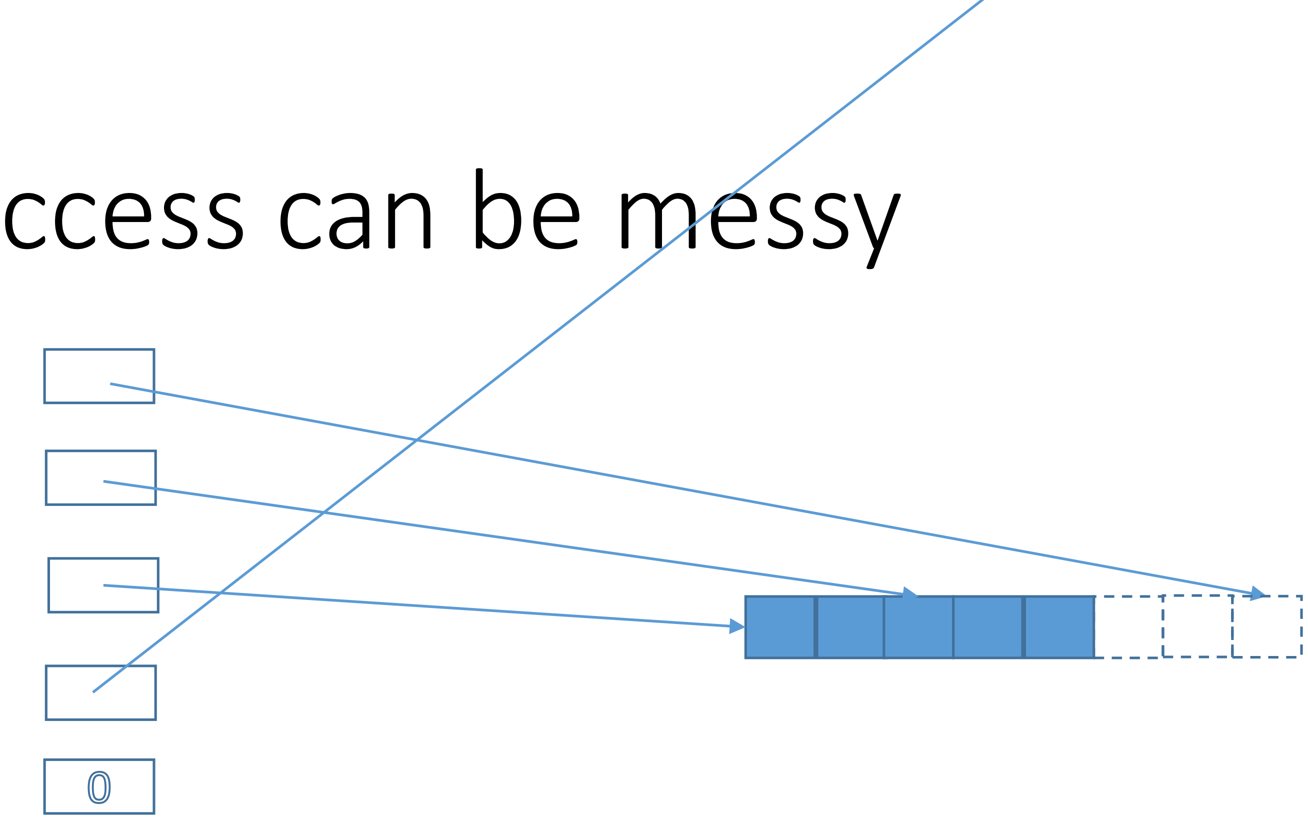
Resource management can be messy



- Objects are not just memory
- Sometimes, significant cleanup is needed
  - File handles
  - Thread handles
  - Locks
  - …

Morgan Stanley

Access can be messy



- Pointers can
  - point outside an object (range error)
  - be a **nullptr** (useful, but don’t dereference)
  - be unititialized (bad idea)

Eliminate all leaks and all memory corruption

- Every object is constructed before use
  - Once only
- Every fully constructed object is destroyed
  - Once only
  - Every object allocated by **new** must be **delete**d
  - No scoped object must be **delete**d (it is implicitly destroyed)
- No access through a pointer that does not point to an object
  - Read or write
  - Off the end of an object (out of range)
  - To **delete**d object
  - To “random” place in memory (e.g., uninitialized pointer)
  - Through **nullptr** (originally: “there is no object at address zero”)
  - That has gone out of scope

Current (Partial) Solutions

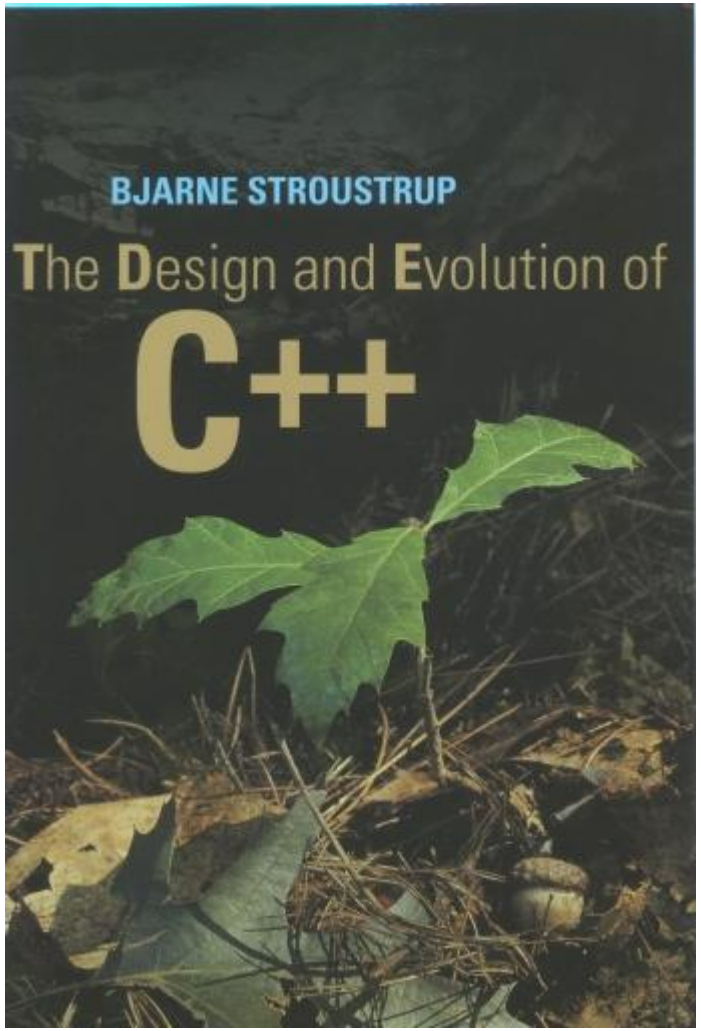
- Ban or seriously restrict pointers
  - Add indirections everywhere
  - Add checking everywhere
- Manual memory management
  - Combined with manual non-memory resource management
- Garbage collectors
  - Plus manual non-memory resource management
- Static analysis
  - To supplement manual memory management
- "Smart" pointers
  - Starting with counted pointers
- Functional Programming
  - Eliminate pointers

Current (Partial) Solutions

- These are old problems and old solutions
  - 40+ years
- Manual resource management doesn’t scale
- Smart pointers add complexity and cost
- Garbage collection is at best a partial solution
  - Doesn’t handle non-memory solutions (“finalizers are evil”)
  - Is expensive at run time
  - Is non-local (systems are often distributed)
  - Introduces non-predictability
- Static analysis doesn’t scale
  - Gives false positives (warning of a construct that does not lead to an error)
  - Doesn’t handle dynamic linking and other dynamic phenomena
  - Is expensive at compile time

Constraints on the solution

- I want it ***now***
  - I don’t want to invent a new language
  - I don’t want to wait for a new standard
- I want it guaranteed
  - “Be careful” isn’t good enough
- Don’t sacrifice
  - Generality
  - Performance
  - Simplicity
  - Portability



A solution

- Be precise about ownership
  - Don’t litter
  - Offer static guarantee
- Eliminate dangling pointers
  - Static guarantee
- Make general resource management implicit
  - Hide every explicit delete/destroy/close/release
  - “lost of explicit annotations” doesn’t scale
    - becomes a source of bugs
- Test for **nullptr** and range
  - Minimize run-time checking
  - Use checked library types
- Avoid other problems with pointers
  - Avoid cast and un-tagged unions

No resource leaks

- We know how
  - Root every object in a scope
    - **vector<T>**
    - **string**
    - **ifstream**
    - **unique_ptr<T>**
    - **shared_ptr<T>**
    - **lock_guard<T>**
  - RAII
    - “No naked **new**”
    - “No naked **delete**”
  - Constructor/destructor
    - “since 1979, and still the best”

Dangling pointers – the worst problem

- One nasty variant of the problem

```
void f(X* p)
{
        // …
        delete p;               // looks innocent enough
}

void g()
{
        X* q = new X;       // looks innocent enough
        f(q);
        // … do a lot of work here …
        q->use();               // Ouch! Read/scramble random memory
}
```

Dangling pointers

- We ***must*** eliminate dangling pointers
  - Or type safety is compromised
  - Or memory safety is compromised
  - Or resource safety is compromised
- Eliminated by a combination of rules
  - Distinguish owners from non-owners
    - E.g., **gsl::owner<int*>**
    - Something that holds an owner is an owner
    - Don’t forget **malloc()**, etc.
  - Assume raw pointers to be non-owners
  - Catch every attempt for a pointer to “escape” into a scope enclosing its owner’s scope
    - **return**, **throw**, out-parameters, long-lived containers, …

Dangling pointers

- Ensure that no pointer outlives the object it points to

```
void f(X* p)
{
        // …
        delete p;               // bad: delete non-owner
}

void g()
{
        X* q = new X;       // bad: assign object to non-owner
        f(q);
        // … do a lot of work here …
        q->use();               // we never get here
}
```

How to avoid/catch dangling pointers

- Rules (giving pointer safety):
  - Basic rule: no pointer must outlive the object it points to
  - Practical rules
    - Don’t transfer to pointer-to-a-local to where it could be accessed by a caller
    - A pointer passed as an argument can be passed back as a result
      - Essential for real-world pointer use
    - A pointer obtained from new can be passed back
      - But we have to remember to eventually delete it

```
int*  f(int* p)
{
        int x = 4;
        return &x;                  // No! would point to destroyed stack frame
        return new int{7};          // OK: doesn’t dangle, but we must “remember” to delete
        return p;                   // OK: came from caller
}
```

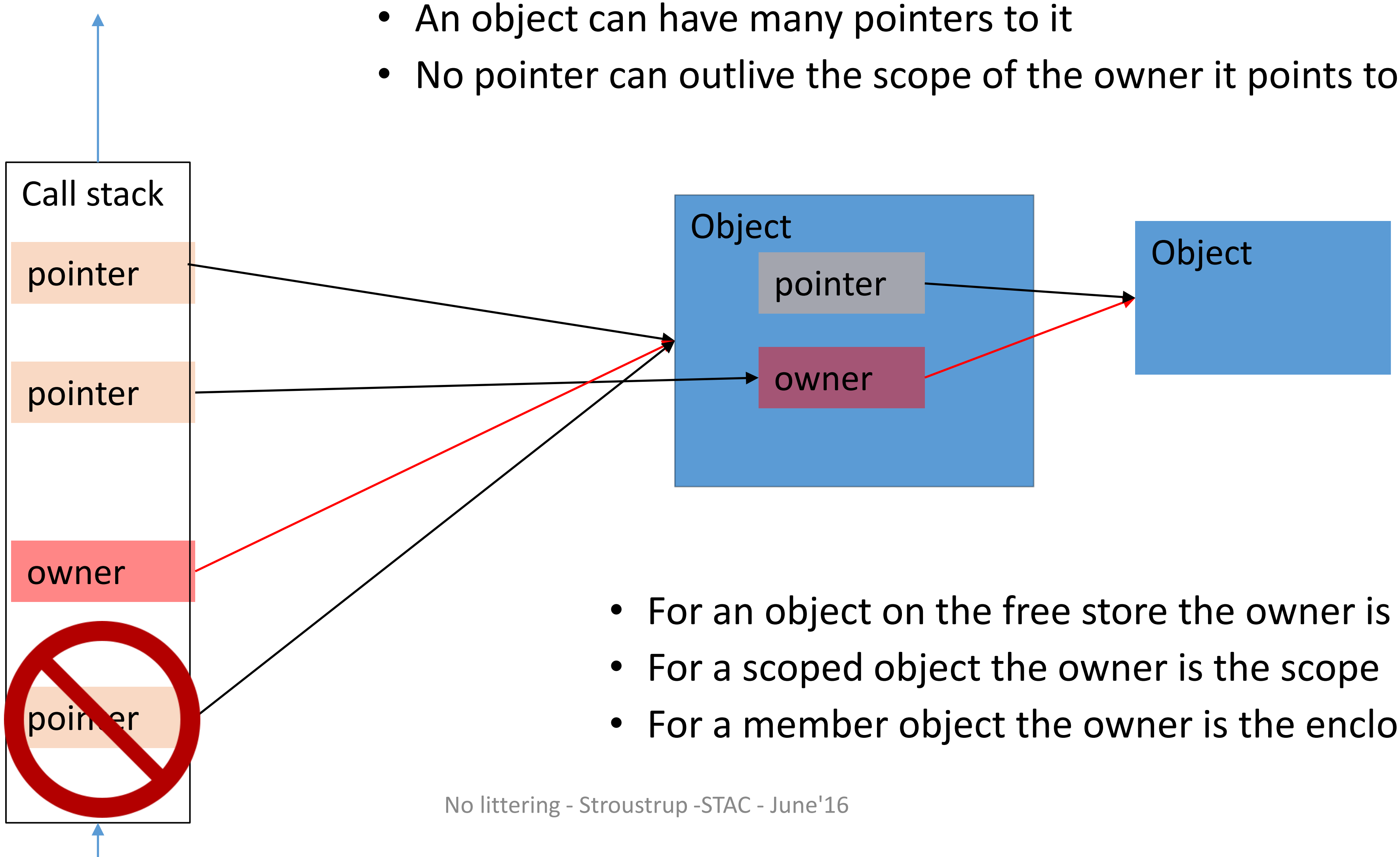
How do we represent ownership?

- Mark an owning **T***: **gsl::owner<T*>**
  - Initial idea (2005 and before)
    - Yet another kind of “smart pointer”
    - **owner<T*>** would hold a **T*** and an “owner bit”
    - Costly: bit manipulation
    - Not ABI compatible
    - Not C compatible
    - Finds errors too late (at run time)
  - So **gsl::owner**
    - Is a handle for static analysis
    - Is documentation
    - Is not a type with it’s own operations
    - Incurs no run-time cost (time or space)
    - Is ABI compatible
    - **template<typename T> using owner = T;**

GSL is our Guidelines Support Library

Owners and pointers

- Every object has one owner
- An object can have many pointers to it
- No pointer can outlive the scope of the owner it points to



- For an object on the free store the owner is a pointer
- For a scoped object the owner is the scope
- For a member object the owner is the enclosing object

How do we manage ownership?

- High-level: Use an ownership abstraction
  - Simple and preferred
    - E.g., **unique_ptr**, **shared_ptr**, **vector**, and **map**
- Low-level: mark owning pointers **owner**
  - An **owner** must be **delete**d or passed to another **owner**
  - A non-**owner** may not be **delete**d
  - This is essential in places but does not scale
  - Applies to both pointers and references

"...And that, in simple terms, is what's wrong with your software design."

How do we manage ownership?

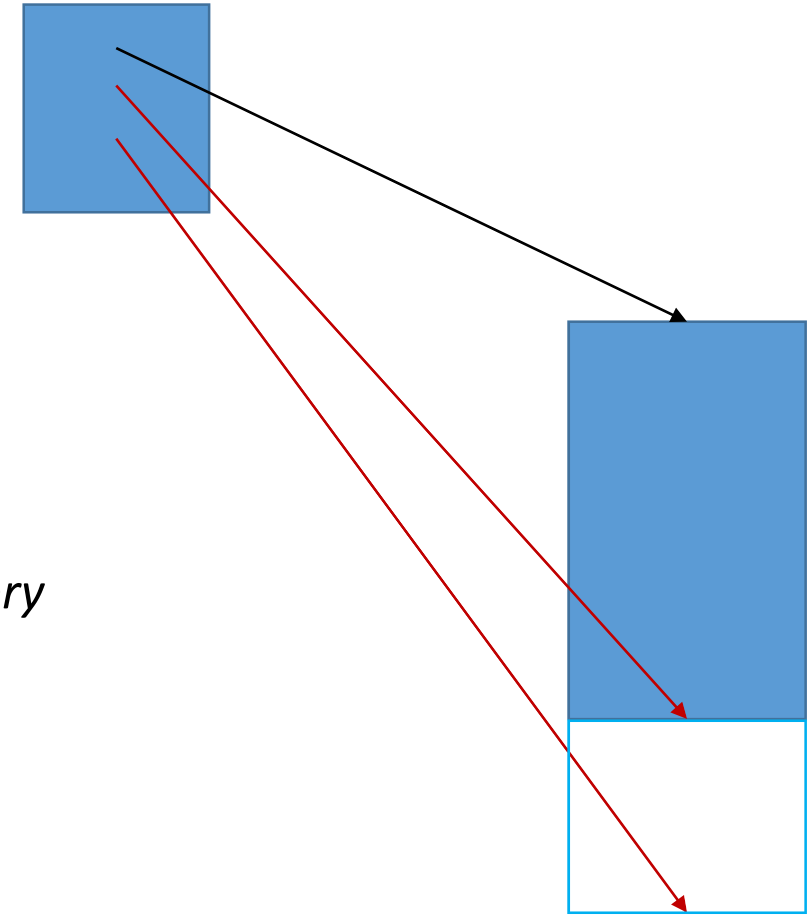
- **owner** is intended to simplify static analysis
  - Necessary inside ownership abstractions
  - **owner**s in application code is a sign of a problem
    - Usually, C-style interfaces
  - "Lots of annotations" doesn't scale
    - Becomes a source of errors

GSL: owner<T>

- How do we implement ownership abstractions?

```
template<SemiRegular T>
class vector {
public:
        // …
private:
        owner<T*> elem;         // the anchors the allocated memory
        T* space;               // just a position indicator
        T* end;                 // just a position indicator
        // …
};
```

- **owner<T*>** is just an alias for **T***



GSL: owner<T>

- How about code we cannot change?
  - ABI stability

```
void foo(owner<int*>);              // foo requires an owner

void f(owner<int*> p, int* q, owner<int*> p2, int* q2)
{
        foo(p);                     // OK: transfer ownership
        foo(q);                     // bad: q is not an owner
        delete p2;                  // necessary
        delete q2;                  // bad: not an owner
}
```

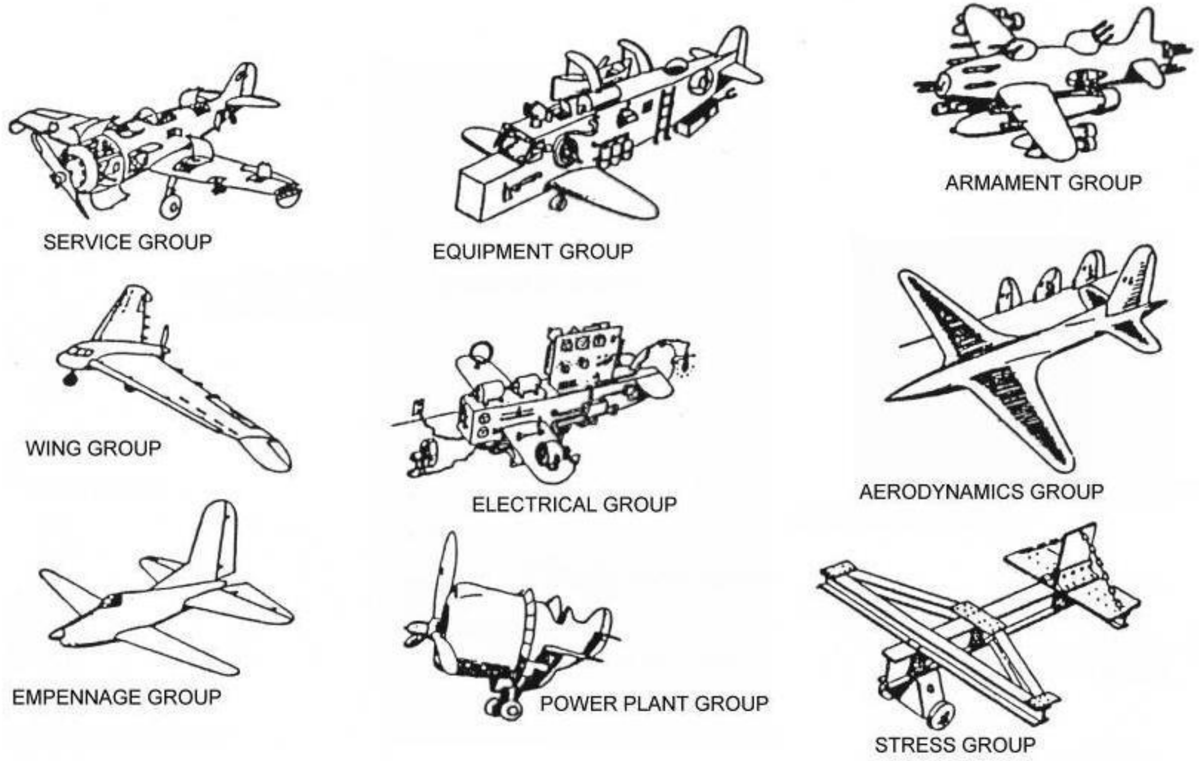
- A static analysis tool can tell us where our code mishandles ownership

Our solution: A cocktail of techniques

- Not a single neat miracle cure
  - Rules (from the “Core C++ Guidelines”)
    - Statically enforced
  - Libraries (STL, GSL)
    - So that we don’t have to directly use the messy parts of C++
  - Reliance on the type system
    - The compiler is your friend
  - Static analysis
    - To extend the type system
- None of those techniques is sufficient by itself
- Enforces basic ISO C++ language rules
- Not just for C++
  - But the “cocktail” relies on much of C++

Details (aka engineering)

- Invention is 1% inspiration and 99% perspiration
- The simple lifetime and ownership model needs to be enforced by many dozens of detailed checks
  - Be comprehensive
  - Minimize false positives
  - Scale to industrial programs
    - Fast analysis is essential – local analysis only
  - Allow for gradual adoption
  - Provide coherent toolsets for all platforms



“Static” is not quite as flexible as “dynamic”

- Classify pointers according to lifetime

```
int glob = 666;

vector<int*> f(int* p)
{
        int x = 4;
        int* q = new int{7};                          // ignore ownership for now
        vector<int*> res = {p, &x, q, &glob};         // potentially bad: mix lifetimes
        return res;                                   // Bad: return { unknown, &local, free store, &global }
}
```

- Don’t mix different lifetimes in an array (overly conservative?)
  - If you must, encapsulate
- Don’t let return statements mix lifetimes

“Static” is not quite as flexible as “dynamic”

- Classify pointers according to ownership

```
int glob = 666;

vector<int*> f(int* p)
{
        int x = 4;
        owner<int*> q = new int{7};
        vector<int*> res = {p, &x, q, &glob};     // potentially bad: mix ownership
        return res;                               // Bad: return {unknown, &local, &owner, &global}
}
```

- Don’t mix different ownerships in an array
    - If you must, encapsulate
- Don’t let different return statements mix ownership

Ownership and pointers

- Owners are a tree
  - Except for **shared_ptr**: a DAG
  - Simple
  - efficient
  - Minimal resource retention
  - No ownership cycles
- Owners can be invalidated
  - Catch simple cases at compile time
  - Use **shared_ptr** and/or **nullptr** checks for not-so-simple cases
- Pointers
  - can only refer to live objects
    - To objects with a live owner
    - To objects “back or to the same level” in a stack
  - can have cycles

Concurrency

- Use scopes and **shared_ptr** to keep threads alive as needed
- A thread is a container (of pointers)
  - The usual rules for containers of pointers apply
  - **std::tread**
    - May or may not outlive its scope
      - Bad
      - we must conservatively assume that it lives forever
  - **gsl::raii_thread**
    - Joins
      - so it is a local container
  - **gsl::detached_thread**
    - Detaches
      - so we must treat it as a non-local container

Owner invalidation

- Some cases are simple

```
void f()
{
        auto p = new int{7};
        delete p;               // invalidate p
        *p = 9;                 // bad: must be prevented
}
```

- Such examples can be handled by static analysis
    - Avoid “naked new” and “naked delete”

Owner invalidation

- Some cases are less simple

```
void g(int* q) { *q = 9; }            // looks innocent

void f()
{
        vecor<int> v {7};
        auto q = &v[0];
        std::thread t {g,q};
        t.detatch();                  // often a bad idea
}

// the thread may outlive v
```

- Such examples can be handled by static analysis
  - Avoid unscoped threads
  - In an emergency, use **shared_ptr** to defeat “false positives”

Owner invalidation

- Some cases are less simple

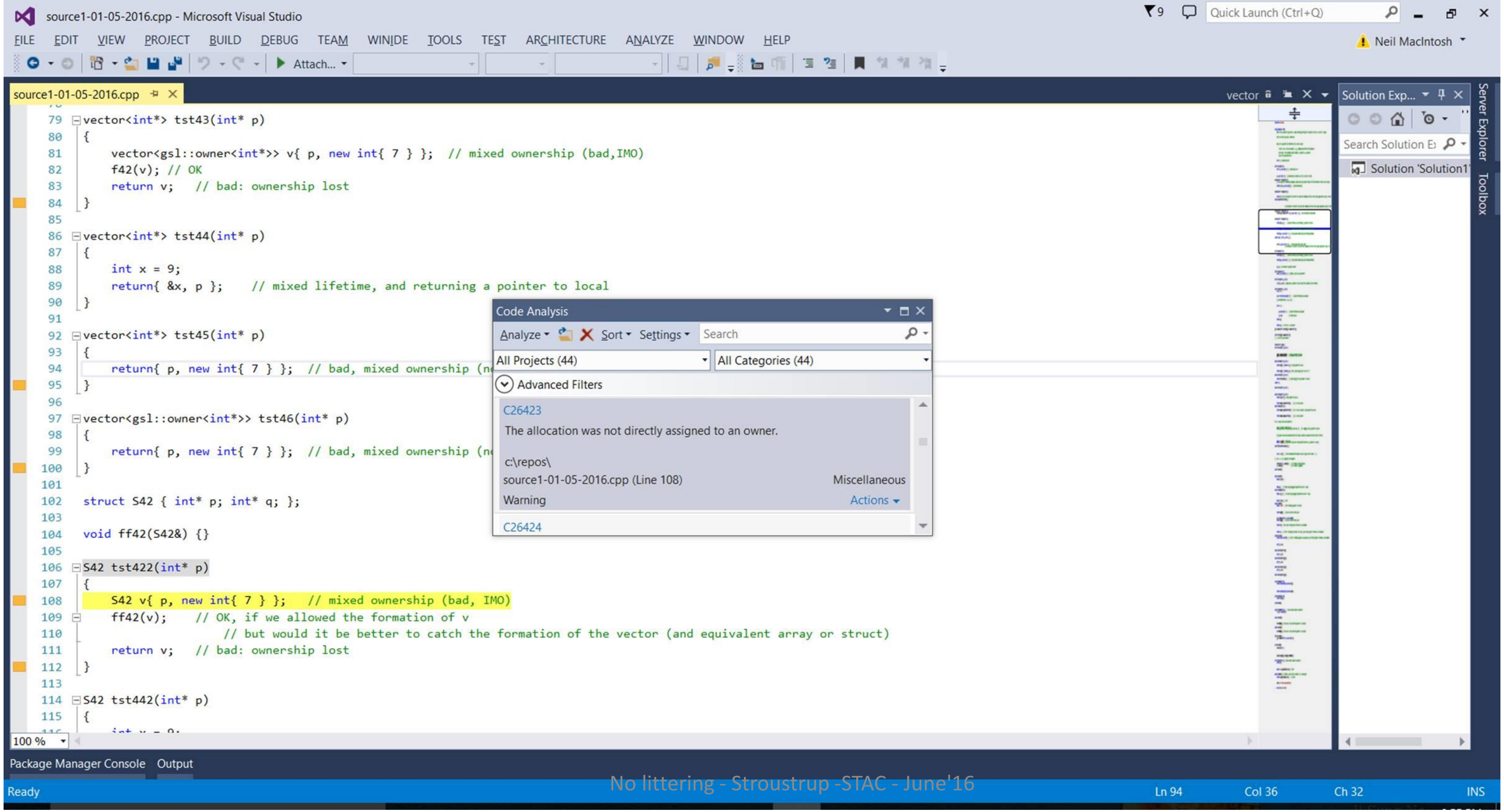
```
void g(int* q) { *q = 9; }          // looks innocent

auto f()
{
        vecor<int> v {7};
        auto q = &v[0];
        return make_shared(thread,g,q);   // bad
}
```

- Such examples can be handled by static analysis

Why not “just use smart pointers”?

- Complexity and (sometimes) cost
    - E.g., different versions of functions for different kinds of pointers
- Use only when you need to manipulate ownership
    - **unique_ptr** for unique ownership
        - guard against exceptions
        - Return pointer-to-base in OOP
    - **shared_ptr** for shared ownership
        - For cases where you can’t identify a single owner
        - ***Not*** for guarding against exceptions
        - ***Not*** for returning objects from the free store
        - More expensive that raw pointers – use counts
        - Can led to need for **weak_ptr**s
        - Can lead to “GC delays”
- Remember
    - Local variables (e.g., handles)
    - Move semantics

Static analysis (integrated)



```
 79  vector<int*> tst43(int* p)
 80  {
 81      vector<gsl::owner<int*>> v{ p, new int{ 7 } };  // mixed ownership (bad,IMO)
 82      f42(v); // OK
 83      return v;   // bad: ownership lost
 84  }
 85
 86  vector<int*> tst44(int* p)
 87  {
 88      int x = 9;
 89      return{ &x, p };    // mixed lifetime, and returning a pointer to local
 90  }
 91
 92  vector<int*> tst45(int* p)
 93  {
 94      return{ p, new int{ 7 } };  // bad, mixed ownership (n
 95  }
 96
 97  vector<gsl::owner<int*>> tst46(int* p)
 98  {
 99      return{ p, new int{ 7 } };  // bad, mixed ownership (n
100  }
101
102  struct S42 { int* p; int* q; };
103
104  void ff42(S42&) {}
105
106  S42 tst422(int* p)
107  {
108      S42 v{ p, new int{ 7 } };   // mixed ownership (bad, IMO)
109      ff42(v);    // OK, if we allowed the formation of v
110                  // but would it be better to catch the formation of the vector (and equivalent array or struct)
111      return v;   // bad: ownership lost
112  }
113
114  S42 tst442(int* p)
115  {
```

C26423
The allocation was not directly assigned to an owner.

c:\repos\
source1-01-05-2016.cpp (Line 108) Miscellaneous
Warning

C26424

Dangling pointer summary

- Simple:
    - Never let a “pointer” escape to where it can refer to its object after that object is destroyed
- It’s not just pointers
    - All ways of “escaping”
        - **return**, **throw**, place in long-lived container, threads, …
    - Same for containers of pointers
        - E.g. **vector<int*>**, **unique_ptr<int>**, **thread**s, iterators, built-in arrays, …
    - Same for references
- We need a formal paper/proof
- We need to demonstrate scaling
    - 1M line code bases

Other problems

- Other ways of breaking the type system
  - Unions: use variant
  - Casts: don’t use them outside abstractions
  - …
- Other ways of misusing pointers
  - Range errors: use **GSL::span<T>**
  - **nullptr** dereferencing: use **GSL::not_null<T>**
- Wasteful ways of addressing pointer problems
  - Misuse of smart pointers
- …
- “Just test everywhere at run time” is ***not*** an acceptable answer
  - We want comprehensive guidelines

GSL::span<T>

- Common interface style
  - major source of bugs

```
void f(int* p, int n)                    // what is n? (How would a tool know?)
{
        p[7] = 9;                                        // OK?
        for (int i=0; i<n; ++i) p[i] = 7;               // OK?
}
```

- Better

```
void f(span<int> a)
{
        a[7] = 9;                                        // OK? Checkable against a.size()
        for (int& x : a) x = 7;                          // OK
}
```

GSL::span<T>

- Common style

```
void f(int* p, int n);
int a[100];
// …
f(a,100);
f(a,1000);     // likely disaster
```

- Better

```
void f(span<int> a)
int a[100];
// …
f(span<int>{a});
f(a);
f({a,1000});   // easily checkable
```

- “Make simple things simple”
  - Simpler than “old style”
  - Shorter
  - At least as fast

nullptr problems

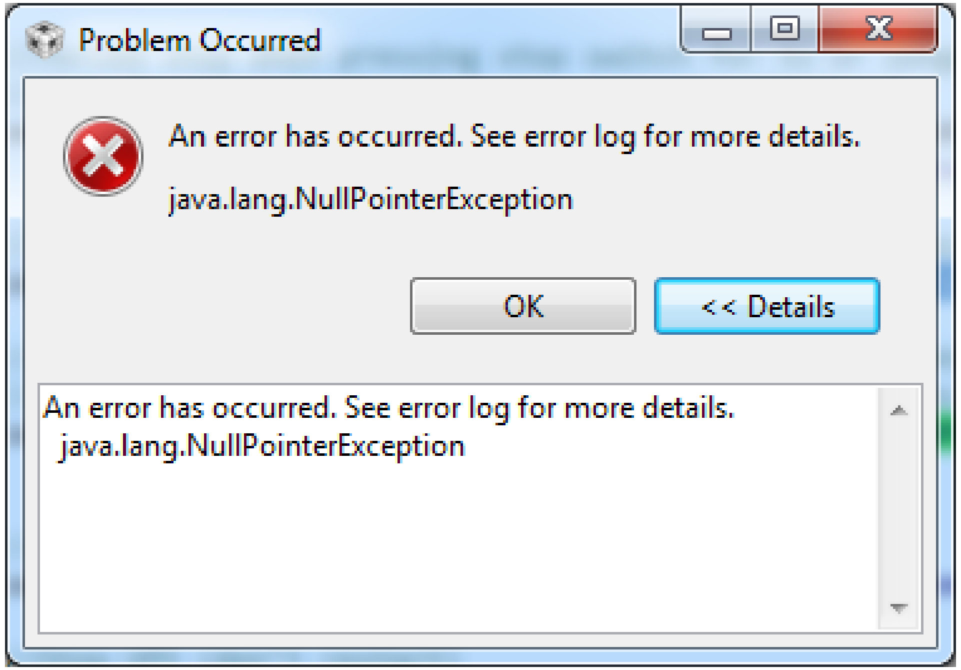
- Mixing **nullptr** and pointers to objects
  - Causes confusion
  - Requires (systematic) checking
- Caller

```
void f(char*);

f(nullptr);              // OK?
```

- Implementer

```
void f(char* p)
{
        if (p==nullptr)      // necessary?
        // …
}
```

- Can you trust the documentation?
- Compilers don’t read manuals, or comments
- Complexity, errors, and/or run-time cost



An error has occurred. See error log for more details.

java.lang.NullPointerException

```
An error has occurred. See error log for more details.
 java.lang.NullPointerException
```

GSL::not_null<T>

- Caller

```
void f(not_null<char*>);

f(nullptr);      // Obvious error: caught be static analysis
char* p = nullptr;
f(p);            // Constructor for not_null can catch the error
```

- Implementer

```
void f(not_null<char*> p)
{
        // if (p==nullptr) // not necessary
        // …
}
```

GSL::not_null<T>

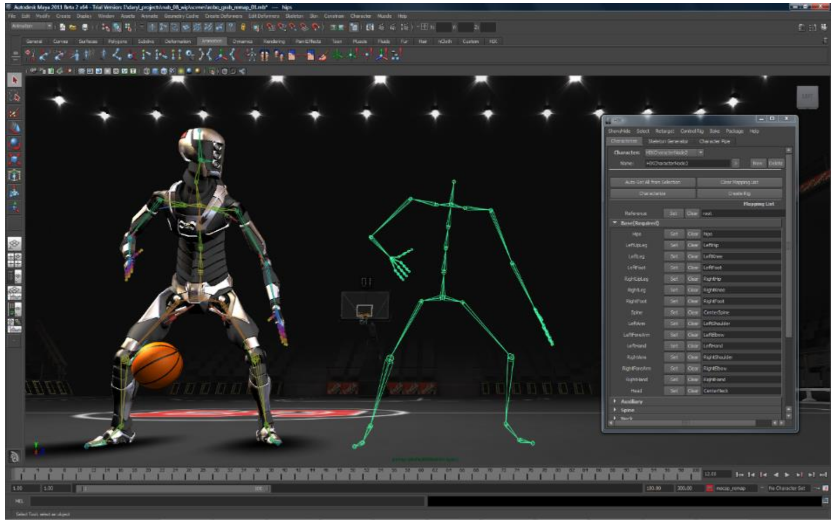
- **not_null<T>**
  - A simple, small class
    - Should it be an alias like **owner**?
  - **not_null<T*>** is **T*** except that it cannot hold **nullptr**
  - Can be used as input to analyzers
    - Minimize run-time checking
  - Checking can be "debug only"
  - For any **T** that can be compared to **nullptr**

To summarize

- Type and resource safety:
  - RAII (scoped objects with constructors and destructors)
  - No dangling pointers
  - No leaks (track ownership pointers)
  - Eliminate range errors
  - Eliminate nullptr dereference
- That done, we attack other sources of problems
  - Logic errors
  - Performance bugs
  - Maintenance hazards
  - Verbosity
  - …

Current state: the game is changing dramatically

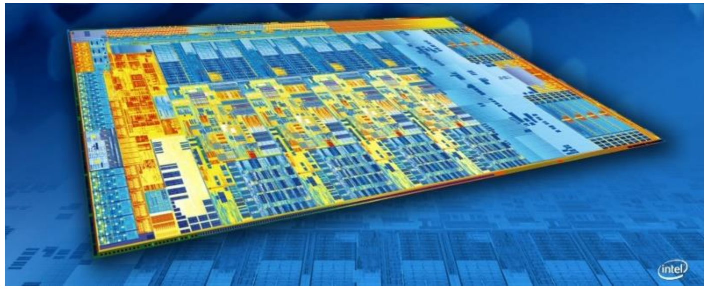
- Papers
  - B. Stroustrup, H. Sutter, G. Dos Reis: A brief introduction to C++'s model for type- and resource-safety.
  - H. Sutter and N. MacIntosh: Preventing Leaks and Dangling
  - T. Ramananandro, G. Dos Reis, X Leroy: A Mechanized Semantics for C++ Object Construction and Destruction, with Applications to Resource Management
- Code (MIT license)
  - https://github.com/isocpp/CppCoreGuidelines
  - https://github.com/microsoft/gsl
  - Static analysis: experimental versions available (Microsoft)
- Videos
  - B. Stroustrup: : Writing Good C++ 14
  - H. Sutter: Writing good C++ 14 By Default
  - G. Dos Reis: Contracts for Dependable C++
  - N. MacIntosh: Static analysis and C++: more than lint
  - N. MacIntosh: A few good types: Evolving array_view and string_view for safe C++ code



We are not unambitious (rough seas ahead)

- Type and resource safety
  - No leaks
  - No dangling pointers
    - No bad accesses
  - No range errors
  - No use of uninitialized objects
  - No misuse of
    - Casts
    - Unions
- We think we can do it
  - At scale
    - 4+ million C++ Programmers, N billion lines of code
  - Zero-overhead principle

Questions?

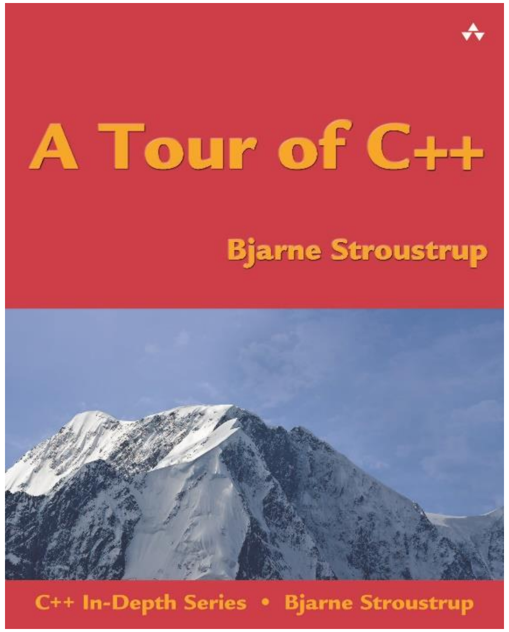


- Type- and Resource-safe C++
  - No garbage collector (because there is no garbage to collect)
  - No runtime overheads (Except necessary range checks)
  - No new limits on expressibility
  - ISO C++
  - Simpler code

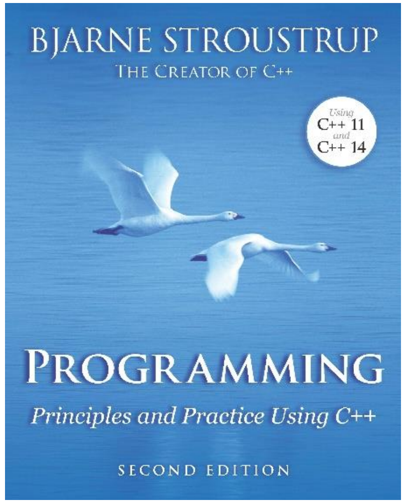
WE DON'T NEED YOUR STINKIN' TRASH
We don't Dump trash where You Live
I'm Bitter about Litter

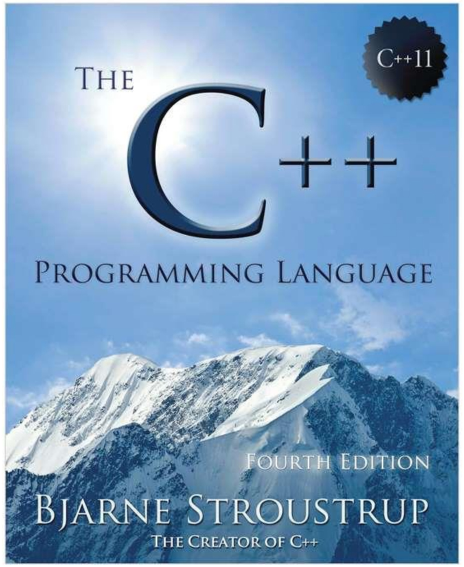
Morgan Stanley

C++ Information



- The C++ Foundation: www.isocpp.org
  - Standards information, articles, user-group information
- Bjarne Stroustrup: www.stroustrup.com
  - Publication list, C++ libraries, FAQs, etc.
  - *A Tour of C++*: All of C++ in 180 pages
  - *The C++ Programming Language (4th edition)*: All of C++ in 1,300 pages
  - *Programming: Principles and Practice using C++ (2nd edition)*: A textbook
- The ISO C++ Standards Committee: www.open-std.org/jtc1/sc22/wg21/
  - All committee documents (incl. proposals)





Videos

- Cppcon: https://www.youtube.com/user/CppCon 2014, 2015
- Going Native: http://channel9.msdn.com/Events/GoingNative/ 2012, 2013

Guidelines: https://github.com/isocpp/CppCoreGuidelines